FLEET TECHNOLOGY LIMITED

TP 10554E

Verification Through Field Measurements of the Extent of Reduction in Icebreaking Resistance for Icebreaking Strakes

by

Fleet Technology Limited

Prepared for:

The Transportation Development Centre
Policy and Coordination Group
Transport Canada

CA1
DTC800-
90
V27

41.D

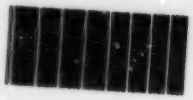
August 1990 C93636

CA1
DTC800-
90
V27

449394

M

41.D



TP 10554E

Verification Through Field Measurements of the Extent of Reduction in Icebreaking Resistance for Icebreaking Strakes

by

D.N. Bruce Cowper
Ron Ritch

Fleet Technology Limited
#16, 6325 11th Street S.E.
Calgary, Alberta T2H 2L6

Prepared for:

The Transportation Development Centre
Policy and Coordination Group
Transport Canada

August 1990

C93636

449394

DDN 449393

91-02516/

The contents of this report reflect the views of Fleet Technology Limited and are not necessarily the official views or opinions of the Transportation Development Centre of Transport Canada or of the Canadian Coast Guard.

Un sommaire en français de ce document est inclus avant la table des matières.

APPROVED BY:

Mr. Ian Glen
President, Fleet Technology Ltd.

PROJECT TEAM

The project team comprised:

For Fleet Technology Limited:

Mr. D.N. Bruce Cowper	Mechanical Engineer, Program Manager
Mr. Ian Glen	Naval Architect, President
Mr. Ron Ritch	Civil Engineer, Project Engineer

For TDC:

Mr. Jacques Laframboise	Project Officer
Mr. Mike Stenson	Project Officer

For the Canadian Coast Guard:

Mr. Daniel Gauvin	Coast Guard Representative

For Kristi Maritime:

Mr. John Carter	Naval Architect

Transport Canada / Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No.	2. Project No.	3. Recipient's Catalogue No.
TP 10554E		

4. Title and Subtitle	5. Publication Date
Verification Through Field Measurements of the Extent of Reduction in Icebreaking Resistance for Icebreaking Strakes	August 1990
	6. Performing Organization Document No. C93636C
7. Author(s)	8. Transport Canada File No.
D.N. Bruce Cowper and Ron Ritch	D1460-2239-3
9. Performing Organization Name and Address	10. DSS File No.
Fleet Technology Limited 16, 6325 11th Street S.E. Calgary, Alberta T2H 2L6	XSD89 - 00150-(673)
	11. DSS or Transport Canada Contract No. T8200-9-9567/01-XSD
12. Sponsoring Agency Name and Address	13. Type of Publication and Period Covered
Transportation Development Centre 200 Rene Levesque Blvd. West, West Tower, Suite 601 Montreal, Quebec H2Z 1X4	Final (Feb. 90/May 90)
	14. Project Officer M. Stenson/J. Laframboise

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

16. Abstract

The potential reduction in ice resistance for non-optimal icebreaking bow forms by the addition of bow strakes has been demonstrated analytically. The strakes, comprising continuous appendages protruding 500 mm from the hull and of triangular shape in section, are attached near the shoulder of the bow, both port and starboard, and intersecting the icebreaking water line. They are designed to decrease the icebreaking resistance by breaking the ice in a bending rather than a crushing mode.

A limited number of full-scale trials were conducted in level unbroken ice on the Saguenay River from the 5th to the 9th of February, 1990, to measure the effect that bow strakes have on the icebreaking performance of the Type 1100 light icebreaking vessel CCGS Sir Wilfrid Laurier. The onboard instrumentation system measured shaft torque, thrust, and rpm on both shafts, as well as ship speed. In addition, the ice thickness, salinity, and temperature were measured. Photographs and video records were made during the trials, showing the interaction of the strakes with the ice.

The data collected were insufficient to determine the effectiveness of the strakes in reducing ice resistance. From an analysis of the video taken the strakes appeared to be too far aft and too high above the operating water line to be fully effective in breaking the ice. In addition it was found that the vessel could not turn appreciably in 0.8 metres of ice.

It is recommended that further tests be conducted with the strakes positioned further forward and lower. In addition, in future full-scale trials cantilever beam tests should be carried out to measure the ice strength.

17. Key Words	18. Distribution Statement
Full-Scale Tests, Propulsion, Resistance	Limited number of copies available from the Transportation Development Centre on request.

19. Security Classification (of this publication)	20. Security Classification (of this page)	21. Declassification (date)	22. No. of Pages	23. Price
Unclassified	Unclassified	-	33	-

TDC/CDT 79-005
Rev 88

Canada

Transports Canada Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. N° de la publication de Transports Canada TP 10554E	2. N° de l'étude	3. N° de catalogue du destinataire
4. Titre et sous-titre **Vérification par le moyen de mesures sur le chantier du degré de réduction dans la résistance due à brisure de la glace pour un brise-glace avec des stries**		5. Date de la publication août 1990 6. N° du document de l'organisme exécutant C93636C
7. Auteur(s) D.N. Bruce Cowper et Ron Ritch		8. N° de dossier — Transports Canada D1460-2239-3
9. Nom et adresse de l'organisme exécutant Fleet Technology Limited 16, 6325 11th Street S.E. Calgary, Alberta T2H 2L6		10. N° de dossier — ASC XSD89 - 00150-(673) 11. N° de contrat — ASC ou Transports Canada T8200-9-9567/01-XSD
12. Nom et adresse de l'organisme parrain Centre de développement des transports 200 Boul. Réné Lévesque ouest, Suite 601, tour ouest, Montréal (Québec) H2Z 1X4		13. Genre de publication et période visée Final (fevrièr à mai 1990) 14. Agent de projet M. Stenson/J. Laframboise
15. Remarques additionnelles (Programmes de financement, titres de publications connexes, etc.)		

16. Résumé

Une étude théorique a permis de déterminer que l'ajout de stries fixées à la proue de navires dont la forme n'a pas été optimisée pour le déglaçage permettrait de réduire la résistance à la marche dans les glaces. De section triangulaire et faisant une saillie de 500 mm sur la coque, ces stries sont fixées à la proue (une par côté) dans la zone de transition reliant celle-ci à la partie rectiligne de la coque, à une hauteur intersectant la ligne de déglaçage. Leur action consiste à réduire la résistance de la glace en agissant sur elle en flexion plutôt qu'en compression.

Un nombre restreint d'essais ont été menés dans les glaces uniformes recouvrant le Saguenay, du 5 au 9 février 1990, dans le but de déterminer la réduction apportée par les stries dans la résistance à la marche d'un brise-glace léger type 1100, en l'occurrence le Sir Wilfrid Laurier. Le système d'acquisition des données à bord a permis d'enregistrer les paramètres suivants: couple moteur, poussée et régime des deux arbres et vitesse du navire. L'épaisseur, la salinité et la température des glaces ont été mesurées. Les photos prises et les enregistrements vidéo faits ont permis de visualiser l'interaction des glaces avec les stries.

L'insuffisance des données recueillies empêche de déterminer l'efficacité de l'action des stries. Par l'analyse de la bande vidéo, on constate que si cette action n'a pas été aussi efficace que prévu c'est parce qu'elles étaient placées trop haut et trop en arrière, par rapport à la ligne de déglaçage. En outre, il a été constaté que le comportement giratoire du navire était inhibé par des glaces de 0,8 m d'épaisseur.

Il est recommandé de procéder à des essais complémentaires, après que les stries auront été déplacées à l'avant et au-dessous de leur position actuelle, et d'effectuer le mesurage précis de la résistance à la rupture en flexion des glaces par la méthode de la poutre à un point d'appui.

17. Mots clés Mots clés: Essais en mer, propulsion, résistance	18. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.			
19. Classification de sécurité (de cette publication) 19. Non classifiée	20. Classification de sécurité (de cette page) Non classifiée	21. Déclassification (date) -	22. Nombre de pages 33	23. Prix -

CDT/TDC 79-005
Rev 88

Canada

ACKNOWLEDGEMENTS

This project was conducted under the auspices of the Transportation Development Centre (TDC) - an agency of Transport Canada - and the Canadian Coast Guard. The TDC Project Officer for this work was Mr. Jacques Laframboise, and the Coast Guard Representative was Mr. Daniel Gauvin. The authors wish to acknowledge both Mr. Laframboise's and Mr. Gauvin's help in defining the project and in providing scientific direction and assistance to the program.

The personnel on the CCGS *Sir Wilfrid Laurier* deserve special acknowledgement. Their highly professional cooperation and assistance with engineering, transportation, accommodation, and logistics contributed immeasurably to its success and timely conduct.

SUMMARY

Recent work sponsored by Transport Canada has indicated the potential reduction in ice resistance for non-optimal icebreaking bow forms by the addition of bow strakes. These strakes are triangular shaped in a section view and are attached near the shoulder of the bow, both port and starboard, and intersecting the icebreaking water line. The main objective of this project was to determine the effect that the recently installed bow strakes have on the icebreaking performance of the CCGS *Sir Wilfrid Laurier*. A limited number of full-scale trials were conducted in level unbroken ice on the Saguenay River in the province of Quebec from the 5th to the 9th of February, 1990.

The instrumentation system deployed measured and recorded the torque, rpm, and thrust for both shaftlines, as well as ship speed. A total of thirteen tests were conducted in relatively constant ice thickness, at a number of ship speeds and power levels. Two continuous turning tests were conducted to evaluate the turning performance of the vessel.

The average ice thickness in this test area ranged from 0.85 to 0.90 metres, with localized areas containing thicker ice. The snow cover ranged from zero to 300 mm, with an average of 100 mm. The average equivalent cantilever beam flexural strength was estimated to be 670 kPa and the Young's Modulus was found to be approximately 1,960 kPa, from salinity and temperature readings of core samples.

The following conclusions are made as a result of these tests:

1. No quantitative conclusions can be made regarding the effectiveness of the bow strakes in improving the icebreaking resistance of the CCGS *Sir Wilfrid Laurier*.

2. Based on an analysis of the video taken it appears that if the strakes were positioned further forward and lower than their present location, they would be more effective in breaking the ice.

3. The bow section of the vessel rises approximately 0.3 - 0.5 metres while level Icebreaking ahead in 0.8 - 0.95 metres of ice. This movement of the bow should be taken into account when deciding upon the optimum position and inclination of bow appendages, such as strakes, used to decrease icebreaking resistance.

It is recommended that additional tests be conducted with the strakes positioned further forward and lower. In additioon in future trials cantilever beam tests of the ice should be done to accurately determine the flexural strength of the ice.

SOMMAIRE

Une recherche récemment achevée, entreprise à la demande de Transports Canada, a montré que l'ajout de stries à la proue de navires dont la forme n'a pas été optimisée pour le déglaçage pourrait réduire la résistance à la marche dans les glaces. De section triangulaire, ces stries sont fixées à la proue (une par côté) dans la zone de transition reliant celle-ci à la partie rectiligne de la coque, à une hauteur intersectant la ligne de déglaçage. La présente recherche avait pour but essentiel de déterminer la réduction apportée par ces stries dans la résistance à la marche, le navire choisi et équipé de stries étant le brise-glace *Sir Wilfrid Laurier* de la Garde côtiére canadienne. Un nombre restreint d'essais ont été menés dans les glaces uniformes du Saguenay au (Québec), du 5 au 9 février 1990.

Le système d'acquisition de données à bord a permis d'enregistrer les paramètres suivants: couple et régime moteur, poussée exercée par les deux arbres et la vitesse. Les essais au nombre de treize ont été menés dans des glaces d'épaisseur relativement uniforme, à des vitesses et des régimes de puissance variés. Enfin, deux essais de giration continue ont été effectués dans le but d'évaluer les performances giratoires du navire.

A l'endroit choisi pour les essais, l'épaisseur moyenne des glaces était de 85 à 90 cm, et même plus en certains endroits. La couverture de neige variait entre 0 et 300mm, la moyenne étant de 100 mm. La résistance moyenne à la rupture en flexion de la glace a été estimée comme équivalant à 670 kPa (méthode de la poutre à un point d'appui) et le module de Young a été établi comme étant de 1 960 kPa environ, à partir des valeurs de salinité et de température des carottes obtenues à titre d'échantillons.

La recherche a abouti aux conclusions suivantes

1. Aucune valeur chiffrée ne peut être tirée touchant l'aptitude des stries à réduire la résistance à la marche dans le cas du *Sir Wilfrid Laurier* .
2. L'analyse du film vidéo pris durant les essais montre que les stries auraient eu une action plus efficace si elles avaient été fixées un peu plus à l'avant et au©dessous de leur position actuelle.
3. La proue du navire s'élève de 0,3 à 0,5 mètre environ lorsqu'il avance dans des glaces uniformes de 0,8 à 0,95 mètre d'épaisseur. Ce mouvement doit être pris en compte dans le calcul du positionnement et de l'inclinaison optimums des stries.

Il est recommandé de procéder à des essais complémentaires, après que les stries auront été déplacées à l'avant et au-dessous de leur position actuelle, et d'effectuer le mesurage précis de la résistance à la rupture en flexion des glaces par la méthode de la poutre à un point d'appui.

TABLE OF CONTENTS

Page

1. INTRODUCTION 1

2. INSTRUMENTATION 2

3. FIELD TRIALS 4

4. ICE CONDITIONS 6

5. RESULTS 18

   5.1 Level Icebreaking Ahead 18

   5.2 Turning Performance 27

   5.3 Analysis of Video 27

6. CONCLUSIONS AND RECOMMENDATIONS 32

7. REFERENCES 33

List of Tables

Table 4.1 Ice Profile Raw Data 13
Table 4.2 Ice Salinity and Temperature Profile Data, Cores 1 - 3 14
Table 4.3 Ice Salinity and Temperature Profile Data, Cores 4 - 6 15
Table 4.4 Sample Calculation of Ice Strength 16
Table 5.1 Summary of Test Measurements 19
Table 5.2 Test Results Adjusted for Ice Thickness and Thrust Deduction 20
Table 5.3 Turning Performance Data: Run 1 30
Table 5.4 Turning Performance Data: Run 2 31

List of Figures

Figure 4.1 February 7 Test Area, Tracks 1 and 2 9
Figure 4.2 February 8 Test Area, Tracks 3 and 4 10
Figure 4.3 Ice Thickness Profiles, Tracks 1 and 2 11
Figure 4.4 Ice Thickness Profiles, Tracks 3 and 4 12
Figure 4.5 Sea Ice Strength In Situ Cantilever Beam Tests 17
Figure 5.1 Total Shaft Power Versus Ship Speed: All Data 21
Figure 5.2 Total Net Thrust Versus Ship Speed: All Data 22
Figure 5.3 Total Shaft Power Versus Ship Speed: Selected Data 24
Figure 5.4 Total Net Thrust Versus Ship Speed: Selected Data 25
Figure 5.5 Turning Performance Test Results: Run 1 28
Figure 5.6 Turning Performance Test Results: Run 2 29

NOMENCLATURE

υ	=	Brine volume (ppt)
S	=	Salinity (ppt)
t	=	Temperature (°C)
σ	=	Strength of sea ice
σ_o	=	Extrapolated strength of sea ice of zero salinity (850 kPa)
K	=	Empirical constant .072 for $\sqrt{\upsilon} < 11.1$
υ	=	Brine volume (ppt)
E	=	Strain modulus (kPa)
E_o	=	Strain modulus of sea ice of zero salinity (2030 kPa)
HPc	=	Adjusted horsepower
Tc	=	Adjusted thrust
Tcn	=	Adjusted net thrust

1. INTRODUCTION

Recent work sponsored by the Transportation Development Centre (TDC) has indicated the potential reduction in ice resistance for non-optimal icebreaking bow forms by the addition of bow strakes. These strakes are triangular shaped in a section view, with a width of approximately 500 mm, and a length of approximately 2 metres. They are attached near the shoulder of the bow, both port and starboard, and intersecting the icebreaking water line (1). They were designed with the aid of the level ice resistance prediction model, developed by Dr. Donald Carter, to decrease the icebreaking resistance by breaking more of the ice in a bending mode rather than a crushing mode. This model predicted that the decrease in ship resistance in level icebreaking operations can be up to 30% for relatively thick ice.

A limited number of full-scale trials were conducted in level ice to measure the effect of bow strakes on the icebreaking performance of the Type 1100 light icebreaking vessel CCGS *Sir Wilfrid Laurier*. The trials were conducted in level unbroken ice on the Saguenay River from the 5th to the 9th of February, 1990.

The CCGS *Sir Wilfrid Laurier* is a diesel electric vessel having two propellers each driven by a variable frequency A.C. motor rated for 3,500 HP at 160 rpm. The four bladed fixed pitch propellers are outboard turning and of Stone Manganese "Meridian" design.

This report describes the instrumentation employed, provides details of the field trials conducted, lists the ice conditions, and presents results, conclusions and recommendations.

2. INSTRUMENTATION

The instrumentation system employed on the CCGS *Sir Wilfrid Laurier* was designed to measure and record the power and thrust for both shaftlines, as well as to provide an accurate measurement of ship speed, during level Icebreaking operations. Both the starboard and port tail shafts were instrumented with strain gauges used to measure torque and thrust. In addition shaft rpm pickups were installed directly under the turning gear on each shaft. The shaft power was calculated from the product of the shaft torque and rpm readings. This power was compared to the values obtained from the engine room instrumentation, and the value displayed on the console in the wheel house.

The strain signals were transmitted by FM telemetry to receivers located on the deck in the shaft compartment. A multi-conductor cable, connected to all six sensor outputs (2 each of torque, thrust, and rpm), was run from the shaft compartment to the wheel-house, where it was connected to the data acquisition system.

The data acquisition system used to record these shaft signals consisted of a Hewlett Packard 9816 computer equipped with 2.3 MBytes of RAM and a 16 channel A/D converter card. The system was installed in the aft starboard side of the wheel house. A complete backup system was also on board for replacement parts if necessary. A software package used by Fleet Technology on a number of icebreaker trials was used to control the data acquisition system and analyze the data. During the propulsion performance trials the system was set to scan the six channels of data at 1,000 readings per second, average these readings for a one second time interval, and store the average values to a floppy disk. The typical duration of each test was 300-400 seconds, hence there were 300-400 stored readings for each signal. Selected shaft torque, thrust, and rpm time histories were plotted after each test to check the data. The data was read from the floppy disks using the software package and preliminary analysis was conducted upon returning to Fleet Technology's offices.

The data acquisition system was also used to record high frequency shaft response measurements (Torque, Thrust, rpm) during ice/propeller interaction events. This data was recorded during transit in broken channel, in level ice, and while manoeuvering to the test areas. This data can be added to Transport Canada's growing data base of shaft dynamic response measurements.

The ship speed was measured by three methods:

1. With the aid of a stop-watch and calibrated markers on the side of the vessel, the time taken for an ice feature to pass between the markers was divided into the measured distance between the markers to provide an estimate of the velocity of the vessel.

2. A video camera was installed at the bridge deck and oriented to record the movement of ice past the side of the vessel, along with a time display imprinted on the image. A calibrated grid was recorded on the video tape to provide a distance scale for the measurement of the movement of an ice feature passing through the camera view area. The video tape was played back at slow motion and the average speed was calculated based upon the time for an ice feature to pass through the calibrated grid as viewed by the camera.

3. The ship's speed log was noted during the trials. This speed reading is reasonably accurate provided there is not a significant amount of ice passing under the vessel.

3. FIELD TRIALS

A total of thirteen tests were conducted in relatively constant ice thickness, for a number of ship speeds and power levels. All tests were conducted with the vessel progressing through level ice in a direction perpendicular to the shore line. The test area was determined by examining charts and previous ice condition reports. All the tests were conducted in the same general area, and the ice properties were measured beside the ship track. To determine the minimum power required to progress in the level ice, the vessel was positioned such that contact with the level ice sheet was just maintained; the shaft rpm was gradually increased until forward progress was achieved. This established a minimum base power level for level icebreaking performance tests. The following steps were followed when conducting propulsive performance tests:

1. Manoeuvre the vessel within 2-3 ship lengths from the level unbroken ice sheet.
2. Start data acquisition system.
2. Progress at a constant rpm level towards the ice sheet.
4. Continue ahead in the level ice at a constant rpm until constant speed is maintained for two to three ship lengths.
5. Stop data acquisition system and store data.
6. Repeat Steps 1 - 5 at various rpm levels.

On February 7, 1990, trials were conducted to assess the effectiveness of the strakes in level icebreaking ahead manoeuvres. A total of seven tests were conducted during which two tests exceeded the icebreaking capability of the vessel, and the vessel could not proceed at a constant rate. The speed levels varied between 0.8 and 4.3 knots, with the power level ranging from 3,850 HP to 6,400 HP. On the morning of February 8, 1990 two tests were conducted with the vessel at the same trim as it was on February 7.

To estimate the icebreaking capability of the CCGS *Sir Wilfrid Laurier* without the strakes the vessel was trimmed approximately 0.5 metres by the stern. This trim condition raised the strakes higher out of the water such that less ice would be broken by them. It is recognized that this condition is not directly comparable with a vessel trimmed level and with no strakes. However, in the absence of sufficient, quality data for the unmodified vessel in similar ice conditions, this approach was considered worthy of investigation. Four tests were conducted with the vessel in the trimmed condition. The speed levels

varied between 1.4 and 1.8 knots, with the power level ranging from 4,400 HP to 6,400 HP.

On the evening of February 8, 1990 two tests were conducted to evaluate the turning performance of the vessel. To start each test the vessel was directed down a broken channel at a constant speed. The ship was then turned into the level ice adjacent to the broken track (channel break out) and the headings and speeds were noted every 15 seconds, as it proceeded around a continuous turn in the unbroken ice sheet.

Video pictures were recorded by both fixed and hand-held cameras. The video from the hand-held camera displayed the ice interaction with the bow and the strakes. In some tests personnel were suspended over the side of the vessel in an aluminum cage, by the ship's crane, to obtain video recordings of the ice failure pattern along the hull and in way of the strakes. These videos provided an excellent viewpoint for interpretation of the ice interaction with the hull and strakes. Slide pictures were also taken of the vessel breaking ice, as viewed from the side of the vessel and from the level ice sheet.

The instrumentation system was decommissioned on February 9, 1990 and the personnel disembarked in the afternoon.

4. ICE CONDITIONS

Level icebreaking tests were performed in the ice perpendicular to the main shipping lane on February 7, 1990 off Cap Rouge. Two separate tracks (#1 and #2) were cut at the test area as shown in Figure 4.1. The ship was first positioned perpendicular to the main shipping track, just into the level unbroken ice and stopped. The ice party then went onto the ice and marked out a proposed track by placing marker posts at ship length intervals on the ice. The ice and snow thickness was then measured at each marker post. The ice profile data is listed in Table 4.1 and graphed in Figure 4.3. As indicated in Figure 4.1 three ice core samples (cores 1-3) were taken, two at the beginning of the track and one at the end of the track . The respective ice temperature and salinity profile data are listed in Table 4.2.

At track 2, the Icebreaking trials were performed and then the ship stopped at the end of the track allowing the ice party to go onto the ice. Ice thickness measurements were taken along the track and two core samples (cores 4 and 5) taken at the end of track. The ice profile along the track is shown in Figure 4.3 and the salinity temperature profile data are listed in Table 4.3.

On February 8 the test site was off Pointe Trinite as shown in Figure 4.2. The ice profile data is listed in Table 4.1 and graphed in Figure 4.4. An ice core was taken and the salinity and temperature profile data is listed in Table 4.3.

Ice thickness measurements were performed by drilling a 50 mm diameter hole using augers and a gas powered motor. An ice toggle with a tape measure attached was lowered into the hole and held against the underside of the ice. A reading relative to the underside of the ice was taken visually at the water-ice interface, ice-snow interface, and snow-air interface. Cores were taken using a standard 15 mm core barrel. Once the core was removed it was placed in a core tray and 6 mm holes were then drilled into the core at various intervals to measure the core temperature. Sections of the core were then taken and placed into containers for later salinity analysis. Salinity analysis was performed on board using a Beckman Salinity Meter and Digital thermometer.

Throughout the test area the ice thickness ranged from 0.79 to 1.3 metres with an average of 0.87 metres. The snow cover ranged from 0.0 to 0.3 metres, with an average of 0.1 metre.

The salinity profiles for all sample cores were similar, with a salinity of 1.1 ppt at the surface going to 0.3 ppt near the underside of the ice. The equivalent cantilever beam flexural strength was calculated based on the work done by Lane (2, 3). The average brine volume was determined by dividing the core into layers based on the samples taken and the temperature measurements. The brine volume is calculated from the following formulae:

Temperature range -0.5°C to -2.06°C

$$\upsilon = S\left(-\frac{52.56}{t} - 2.28\right)$$

where υ = Brine volume (ppt)
S = Salinity (ppt)
t = Temperature (°C)

Temperature range -2.06°C to -8.2°C

$$\upsilon = S\left(-\frac{45.917}{t} + 0.930\right)$$

Temperature range -8.2°C to -22.9°C

$$\upsilon = S\left(-\frac{43.795}{t} + 1.189\right)$$

The equivalent cantilever beam flexural strength was then calculated using Lane's formula.

$$\sigma = \sigma_0 (1 - K \sqrt{\upsilon})$$

where σ = strength of sea ice
σ_0 = extrapolated strength of sea ice of zero salinity 850kPa
K = empirical constant .072 for $\sqrt{\upsilon} < 11.1$
υ = Brine volume (ppt)

Table 4.4 shows a sample calculation of cantilever beam strength. The average equivalent cantilever beam flexural strength was calculated to be 670 kPa.

The strain Modulus was calculated based on Lane's work using the formula;

$$E = E_o (1 - \upsilon/1000)^4$$

where E = strain modulus (kPa)
E_o = strain modulus of sea ice of zero salinity, 2030 (kPa)
υ = Brine volume (ppt)

The strain modulus was calculated to be 1,960 kPa.

Lane's formulation for cantilever beam flexural strength is a linear least square fit of available sea ice data as shown in Figure 4.5. As can be seen in the figure all of the data used has brine volumes greater than 16 ($\sqrt{\upsilon}>4$) whereas the brine volume for the current test samples ranged from 5 to 13. In order to check the applicability of Lane's formulation for the Saguenay, literature was reviewed for cantilever tests conducted in this area. In 1969 Michel (4, 5) conducted cantilever beam tests at Baie des Ha! Ha! on the Saguenay river and tests were conducted by Arctec Canada (6) in the same area in 1979. These two data points are plotted on Figure 4.5. The measured field data lie near the line based on Lane's formulation and, therefore, Lane's formulation is considered applicable for the data collected on these trials.

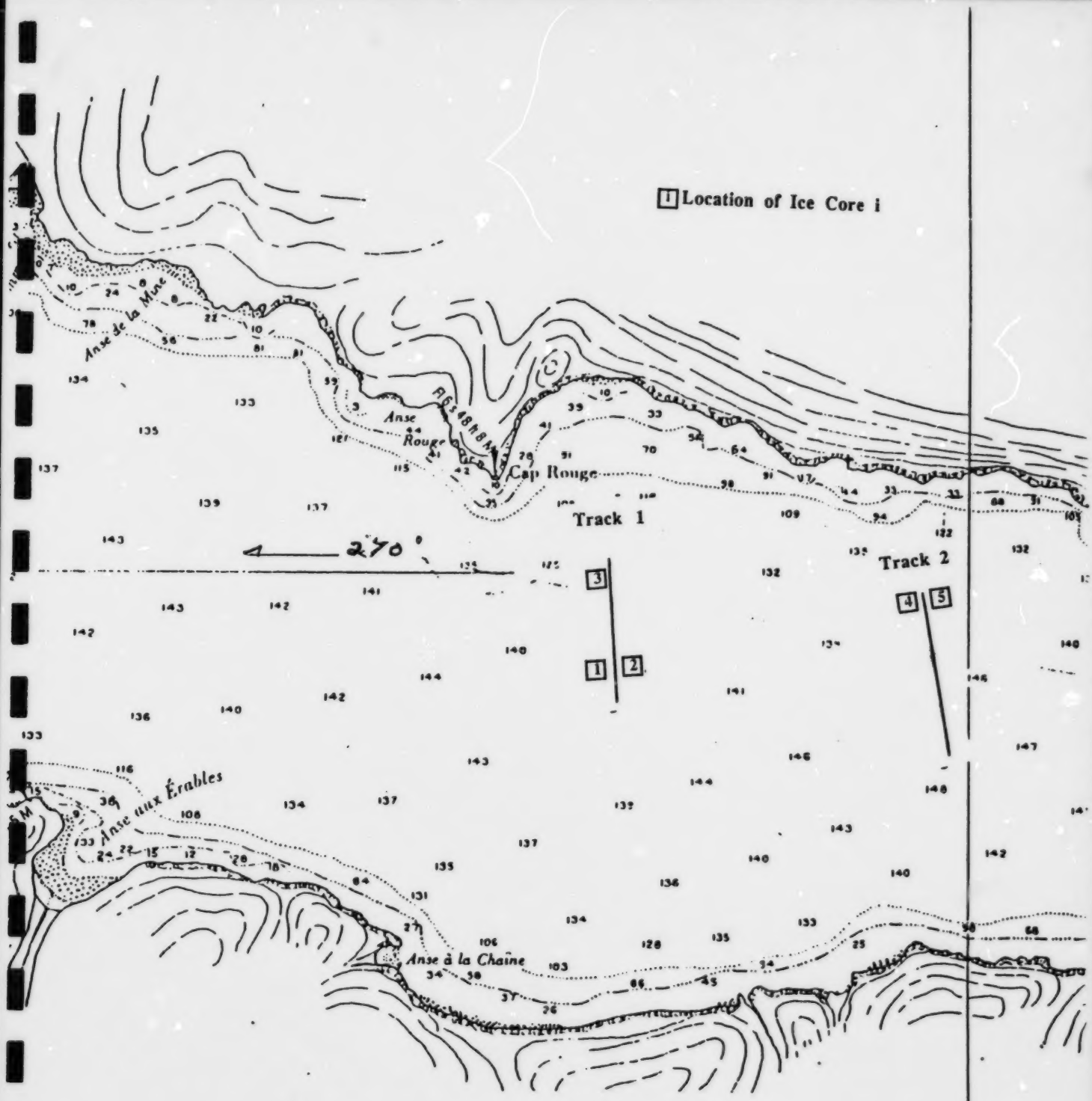


Figure 4.1 February 7 Test Area, Track 1 and 2

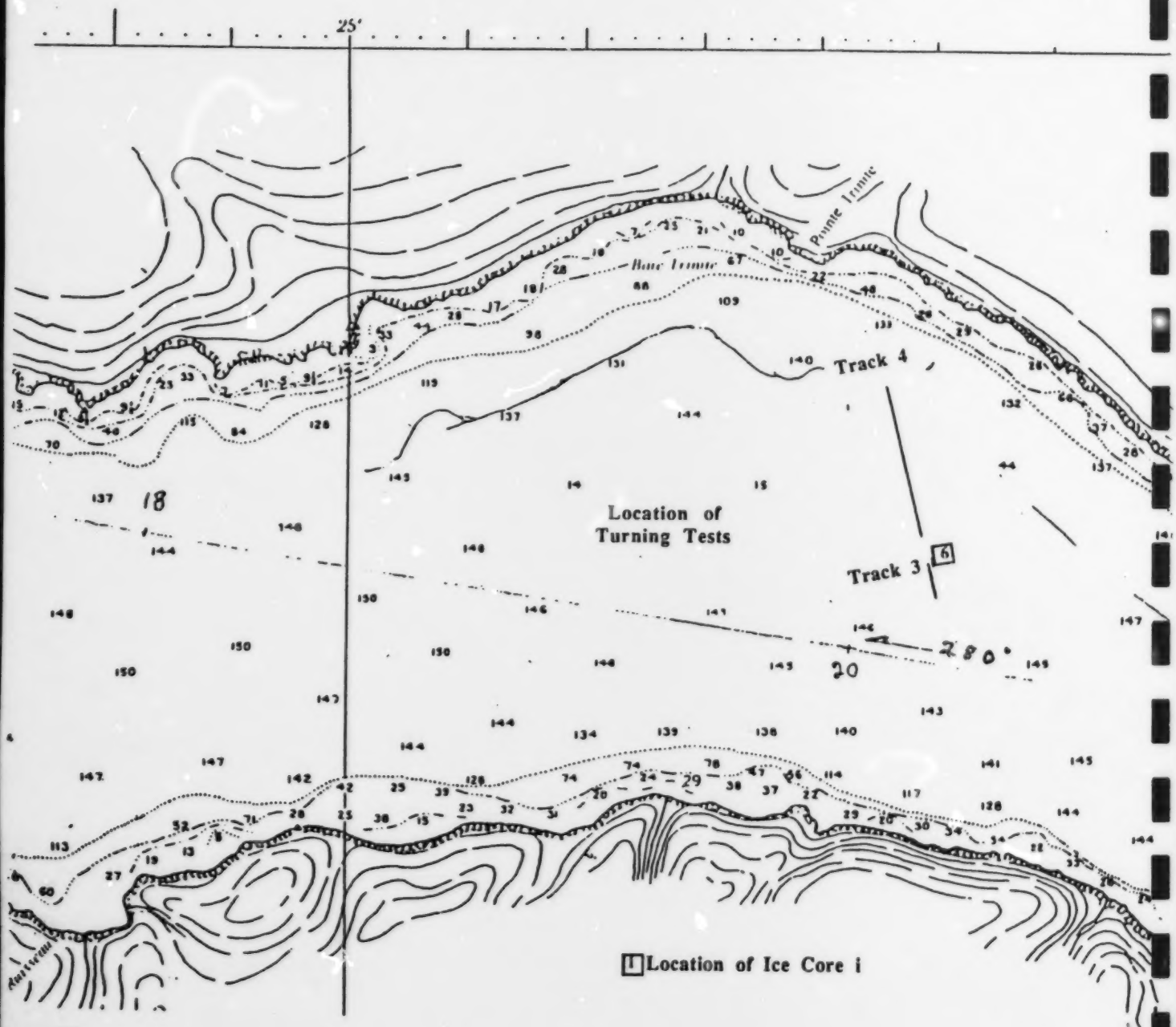
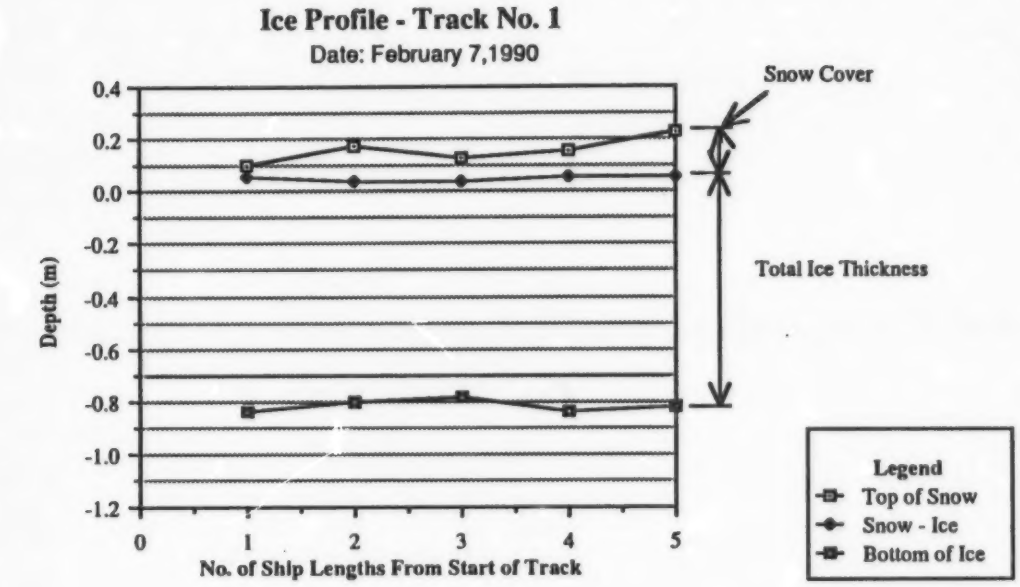


Figure 4.2 February 8 Test Area, Track 3 and 4



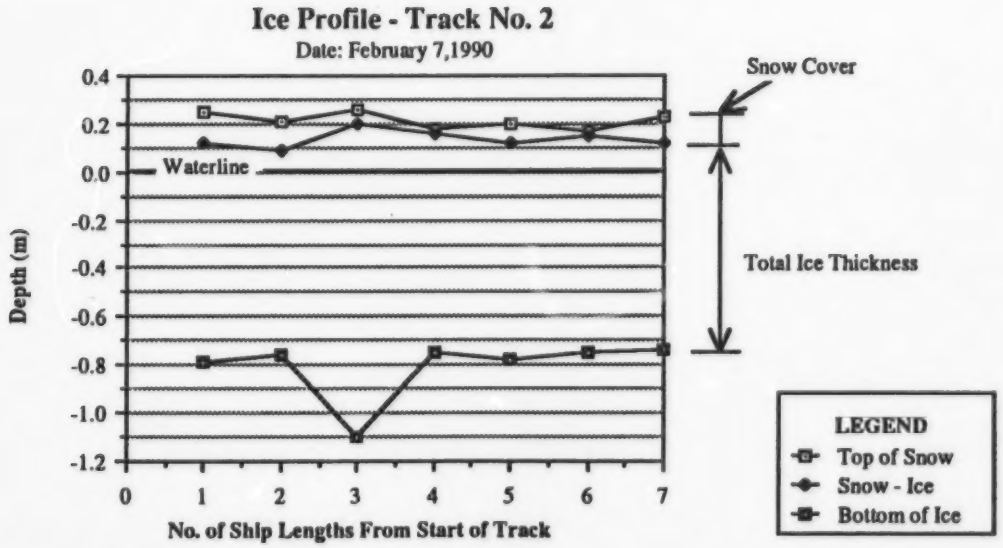
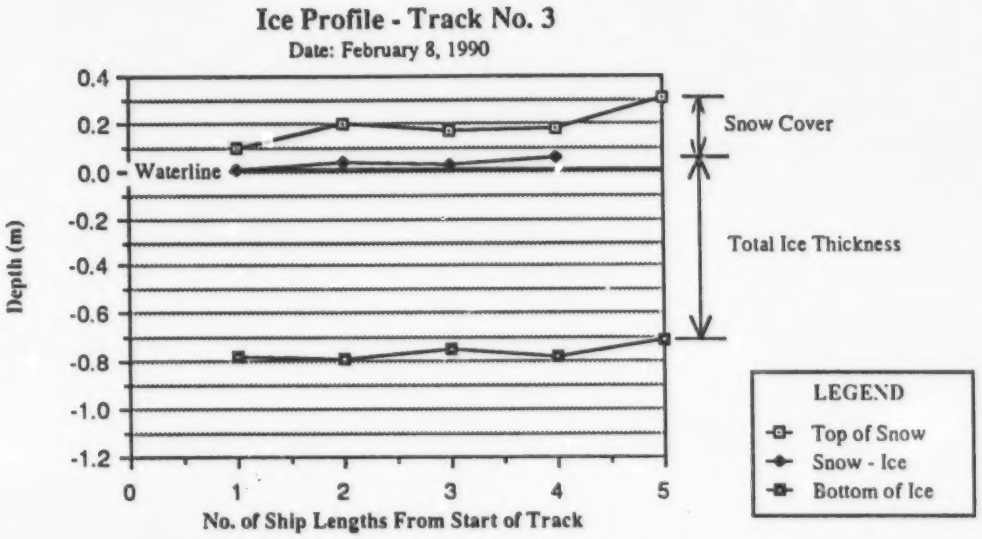


Figure 4.3 Ice Thickness Profiles, Tracks 1 and 2



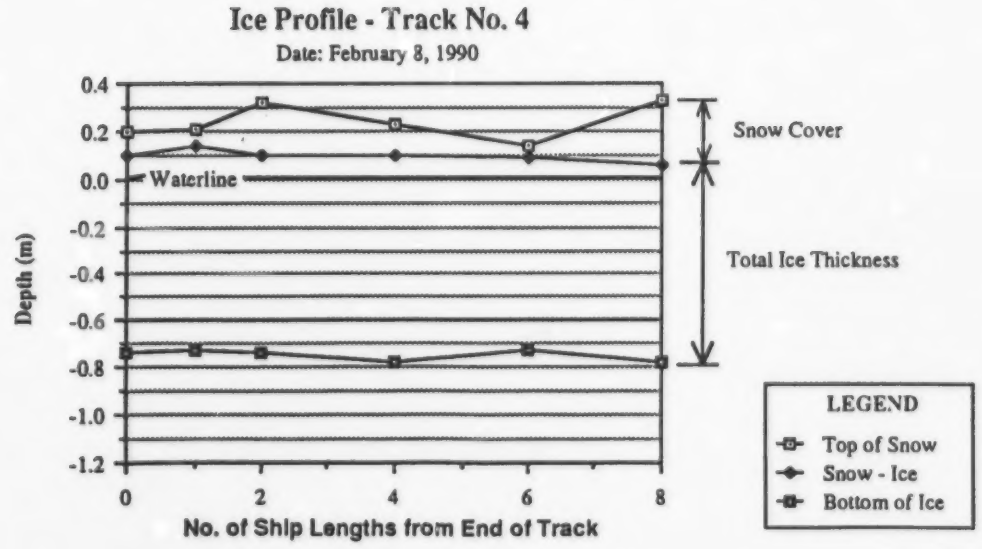


Figure 4.4 Ice Thickness Profiles, Tracks 3 and 4

Table 4.1 Ice Profile Raw Data

Ice Profile - Track Number 1, February 7, 1990

Number of Ship Lengths From Start of Track	Depth of Ice Below Waterline (m)	Snow - Ice Interface From the Bottom of the Ice (m)	Top of Snow from the Bottom of the Ice (m)	Total Ice Thickness (m)	Snow Thickness (m)
1	0.84	N/A	0.94	N/A	N/A
2	0.80	0.84	0.97	0.84	0.13
3	0.78	0.82	0.91	0.82	0.09
4	0.84	0.90	1.00	0.90	0.10
5	0.82	0.90	1.05	0.90	0.15
Average/STD				0.87/0.04	0.12/0.03

Ice Profile - Track Number 2, February 7, 1990

Number of Ship Lengths From Start of Track	Depth of Ice Below Waterline (m)	Snow - Ice Interface From the Bottom of the Ice (m)	Top of Snow from the Bottom of the Ice (m)	Total Ice Thickness (m)	Snow Thickness (m)
1	0.73	0.86	0.92	0.86	0.06
2	0.74	0.86	0.97	0.86	0.11
3	0.75	0.90	0.92	0.90	0.02
4	0.78	0.90	0.98	0.90	0.08
5	0.75	0.91	0.93	0.91	0.02
6	0.76	1.30	1.36	1.30	0.06
7	0.79	0.85	0.97	0.85	0.12
8	1.10	0.91	1.04	0.91	0.13
Average/STD				0.94/0.15	0.08/0.04

Ice Profile - Track Number 3, February 8, 1990

Number of Ship Lengths From Start of Track	Depth of Ice Below Waterline (m)	Snow - Ice Interface From the Bottom of the Ice (m)	Top of Snow from the Bottom of the Ice (m)	Total Ice Thickness (m)	Snow Thickness (m)
1	0.71	0.79	0.88	0.79	0.09
2	0.78	0.83	0.99	0.83	0.16
3	0.75	0.78	0.92	0.78	0.14
4	0.79	0.84	0.96	0.84	0.12
5	0.78	1.01	1.02	1.01	0.01
Average	0.76	0.85	0.95	0.85/0.09	0.10/0.06

Ice Profile - Track Number 4, February 8, 1990

Number of Ship Lengths From Start of Track	Depth of Ice Below Waterline (m)	Snow - Ice Interface From the Bottom of the Ice (m)	Top of Snow from the Bottom of the Ice (m)	Total Ice Thickness (m)	Snow Thickness (m)
0	0.74	0.84	0.94	0.84	0.10
1	0.73	0.87	0.94	0.87	0.07
2	0.74	0.84	1.06	0.84	0.22
4	0.78	0.88	1.01	0.88	0.13
6	0.73	0.82	0.87	0.82	0.05
8	0.78	0.84	1.11	0.84	0.27
Average/STD				0.85/0.02	0.11/0.06

Table 4.2 Ice Salinity and Temperature Profile Data, Cores 1-3

Ice Core Sample No. 1
Date: Feb. 7, 1990 Time:08:00
Location: Track 1, 1 Ship length ahead of bow
Air Temperature: -10.2
Ice Thickness: 0.84 m

Temperature Profile

Distance from Top (mm)	Temperature (C)
150	-12.2
240	-8.3
320	-8.4
390	-7.4
460	-4.9
580	-2.3

Salinity Profile

Range of Core Sampled (mm)	Salinity (ppt)
120-200	0.70
270-340	0.90
440-490	0.40
550-620	0.50

Ice Core Sample No. 2
Date: Feb. 7, 1990 Time:8:00
Location: Track 1, 1 Ship length ahead of bow
Air Temperature: -10.2
Ice Thickness: 0.84 m

Temperature Profile

Distance from Top (mm)	Temperature (C)
170	-8.2
260	-6.7
350	-5.9
440	-5.2
520	-4.0
620	-3.4

Salinity Profile

Range of Core Sampled (mm)	Salinity (ppt)
140-210	1.20
230-300	0.90
400-470	0.45
570-640	0.58

Ice Core Sample No.3
Date: Feb. 7, 1990 Time: 9:00
Location: Track 1, 5 Ship length ahead of bow
Air Temperature: -11.2
Ice Thickness: 0.85 m

Temperature Profile

Distance from Top (mm)	Temperature (C)
140	-8.2
240	-6.7
340	-5.9
410	-5.2
500	-4.0
580	-3.4
650	-2.2
720	-1.7
800	-1.1

Salinity Profile

Range of Core Sampled (mm)	Salinity (ppt)
140	1.03
410	0.39
800	0.28

Table 4.3 Ice Salinity and Temperature Profile Data, Cores 4-6

Ice Core Sample No.4
Date: Feb. 7, 1990 Time:16:20
Location: Track 2, at end of track
Air Temperature: -4.2
Ice Thickness: 0.91 m

Temperature Profile

Distance from Top (mm)	Temperature (C)
40	-4.8
120	-4.9
220	-4.4
340	-3.7
440	-2.9
520	-2.1

Salinity Profile

Range of Core Sampled (mm)	Salinity (ppt)
No Samples Taken	

Ice Core Sample No.5
Date: Feb. 8, 1990 Time:16:00
Location: Test area No. 2, at end of track (same place as core 4)
Air Temperature: -4.2 Water Temperature -0.5
Ice Thickness: 0.91 m

Temperature Profile

Distance from Top (mm)	Temperature (C)
40	-5.0
120	-4.8
220	-4.3
320	-3.6
480	-2.9
580	-2.3
640	-1.2

Salinity Profile

Range of Core Sampled (mm)	Salinity (ppt)
0-80	1.30
170-260	0.78
260-380	0.44
380-530	0.45
530-670	0.25

Ice Core Sample No.6
Date: Feb. 8, 1990 Time:10:00
Location: Track 3, at end of track
Air Temperature: -6.0
Water Temperature -0.5
Ice Thickness: 0.85 m

Temperature Profile

Distance from Top (mm)	Temperature (C)
40	-3.7
120	-3.2
220	-2.8
340	-2.4
420	-1.6
510	-1.2

Salinity Profile

Range of Core Sampled (mm)	Salinity (ppt)
0-70	0.73
70-160	0.82
160-250	1.22
310-380	0.35
390-480	0.43
480-570	0.30

Table 4.4 Sample Calculation of Ice Strength

Ice Core Sample No. 1
Date: Feb. 7, 1990 Time:08:00
Location: Track 1, 1 Ship length ahead of bow
Air Temperature: -10.2

Temperature data

Measured Data Depth (mm)	Measured Data Temp (Deg. C)	Centre of Layer (mm)	Temp. at Centre (Deg. C)	Portion of Sample At the layer Midpt. Temp.	
0.00	-12.20	0.00			
150.00	-12.20	75.00	-12.20	-2.18	**
240.00	-8.30	195.00	-10.25	-1.10	
320.00	-8.40	280.00	-8.35	-0.80	
390.00	-7.40	355.00	-7.90	-0.66	
460.00	-4.90	425.00	-6.15	-0.51	
580.00	-2.30	520.00	-3.60	-0.51	
840.00	-0.50	710.00	-1.40	-0.43	
			AVERAGE TEMPERATURE	-6.19	

** Sample calc (150-0)/840*-12.2=-2.18

SALINITY DATA

Measured Data Depth (mm)	Measured Data Salinity (ppt)	Centre of layer (mm)	Salinity at Centre of Layer (ppt)	Portion of Sample At the layer Midpt. Temp.
0.00	0.70	0.00		
120.00	0.70	60.00	0.70	0.11
200.00	0.70	160.00	0.70	0.07
270.00	0.90	235.00	0.80	0.07
340.00	0.90	305.00	0.90	0.08
440.00	0.40	390.00	0.65	0.08
490.00	0.40	465.00	0.40	0.03
550.00	0.50	520.00	0.45	0.03
620.00	0.50	585.00	0.50	0.04
840.00	0.50	730.00	0.50	0.14
			AVERAGE SALINITY	0.65

Lane's Formula for brine Volume
Temperature in the range of -2C to -8.2C
brine vol. (Ub) =s(-45.917/t+0.93)
For this case Ub = 5.38

Sigma = 850*(1-k*sqrt(Ub)) (k=0.72)

Sigma = 708 kPa

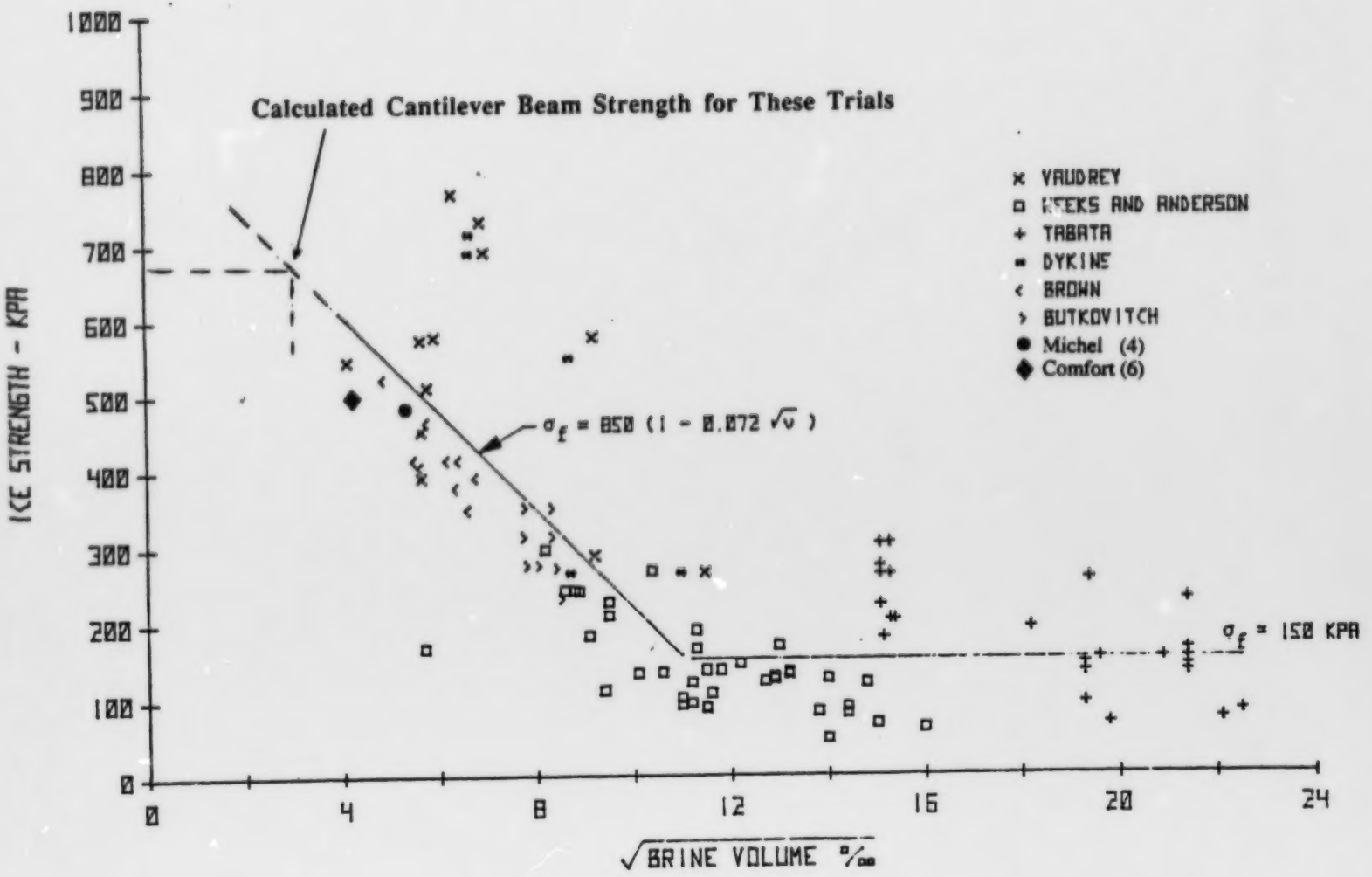


Figure 4.5 Sea Ice Strength In-Situ Cantilever Beam Tests (From Lane (2))

5. RESULTS

5.1 Level Icebreaking Ahead

A summary of the measurements taken are listed in Table 5.1. To enable a comparison to be made on the performance data, horsepower and thrust figures are adjusted to a normalized ice thickness. Ice thickness is first corrected for snow cover and is assumed equal to the measured ice thickness plus one third of the snow cover.

Horsepower and thrust measurements are then adjusted linearly to a normalized ice thickness of 0.883 metres; this thickness being common in six of the thirteen cases and is in the midrange of all thicknesses measured. To be more precise horsepower and thrust should be adjusted based upon ice thickness to a specified exponent. The numerical model developed by Dr. Donald Carter, the "Carter Model", indicates this exponent should be of the order of 1.4 over the speed range tested; however, it is not possible to verify this figure from the full-scale data obtained during these trials. Since the ice thickness variation is within ±10% of the normalized figure any error introduced by assuming a linear relationship between ice thickness and horsepower and thrust is considered negligible.

The adjusted horsepower (HPc) and thrust (Tc) values at the respective measured speeds are listed in Table 5.2 for a normalized ice thickness of 0.883 metres.

To obtain net thrust (ship resistance) produced by the propellers it is necessary to apply a thrust deduction factor to the adjusted shaft thrust values. Since the propeller/ice interaction was observed to be relatively low in frequency an average thrust deduction of 10% is assumed over the speed range. The total net propeller thrust then is indicated in Table 5.2 as Tcn.

A plot of all data for adjusted horsepower (HPc) and adjusted net thrust (Tcn) versus speed is presented in Figures 5.1 and 5.2 respectively. The level and trimmed conditions are noted on these figures. The scatter in the test results is significant and may be attributed, at least in part, to the varying ambient air temperature, and hence a change in the dynamic friction coefficient.

Table 5.1 Summary of Test Measurements

Test No.	Power (HP)	Velocity (knots)	Snow Thick. (m)	Ice Thick. (m)	Shaft Thrust (kN)
1	3200	0.0	0.05	.095	507
2	6400	4.3	0.10	0.85	722
3	3850	0.0	0.10	0.85	633
4	5460	2.1	0.10	0.85	724
5	4200	1.7	0.10	0.85	632
6	6400	2.7	0.10	0.85	795
7	3850	0.8	0.10	0.85	610
8	4700	0.0	0.10	0.80	707
9	5600	1.4	0.15	0.80	746
10	5500	1.8	0.05	0.85	724
11	4400	0.0	0.10	0.90	707
12	5240	1.8	0.20	0.85	710
13	6300	2.9	0.10	0.85	792

NB. Tests 10-13 are for the vessel at the trimmed condition.

Table 5.2 Test Results Adjusted for Ice Thickness and Thrust Deduction

Test No.	Power (HPc) (HP)	Velocity (knots)	Thrust (Tc) (kN)	Net Thrust (Tcn) (kN)
1	2922	0.0	463	417
2	6400	4.3	722	650
3	3850	0.0	633	570
4	5460	2.1	724	652
5	4200	1.7	632	569
6	6400	2.7	795	716
7	3850	0.8	610	549
8	5168	0.0	777	699
9	5817	1.4	775	698
10	5601	1.8	737	663
11	4164	0.0	669	602
12	5046	1.8	684	616
13	6522	2.9	820	738

NB. Adjusted for Ice Thickness of 0.883 m and a Thrust Deduction factor of 0.1.

Figure 5.1 Total Shaft Horsepower vs Ship Speed: All Data

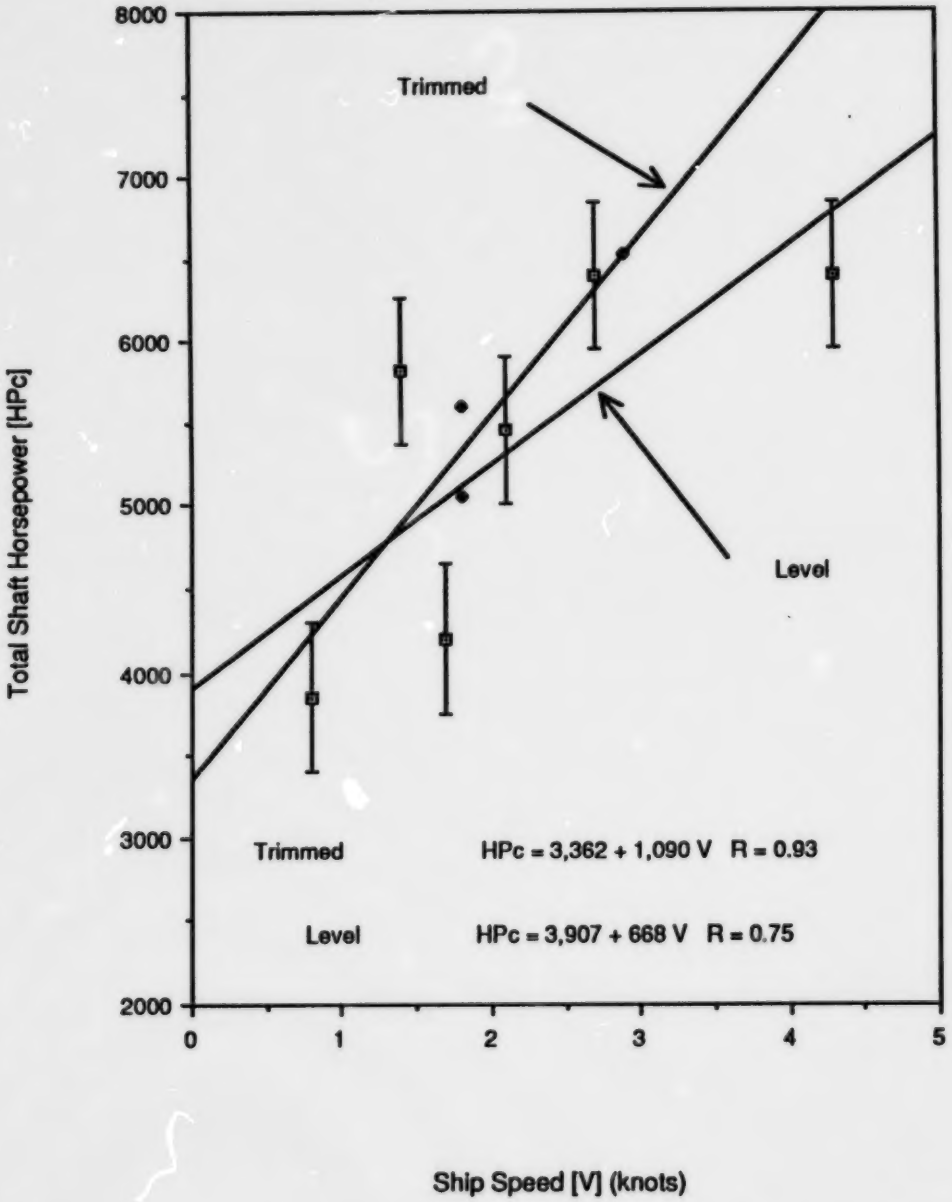
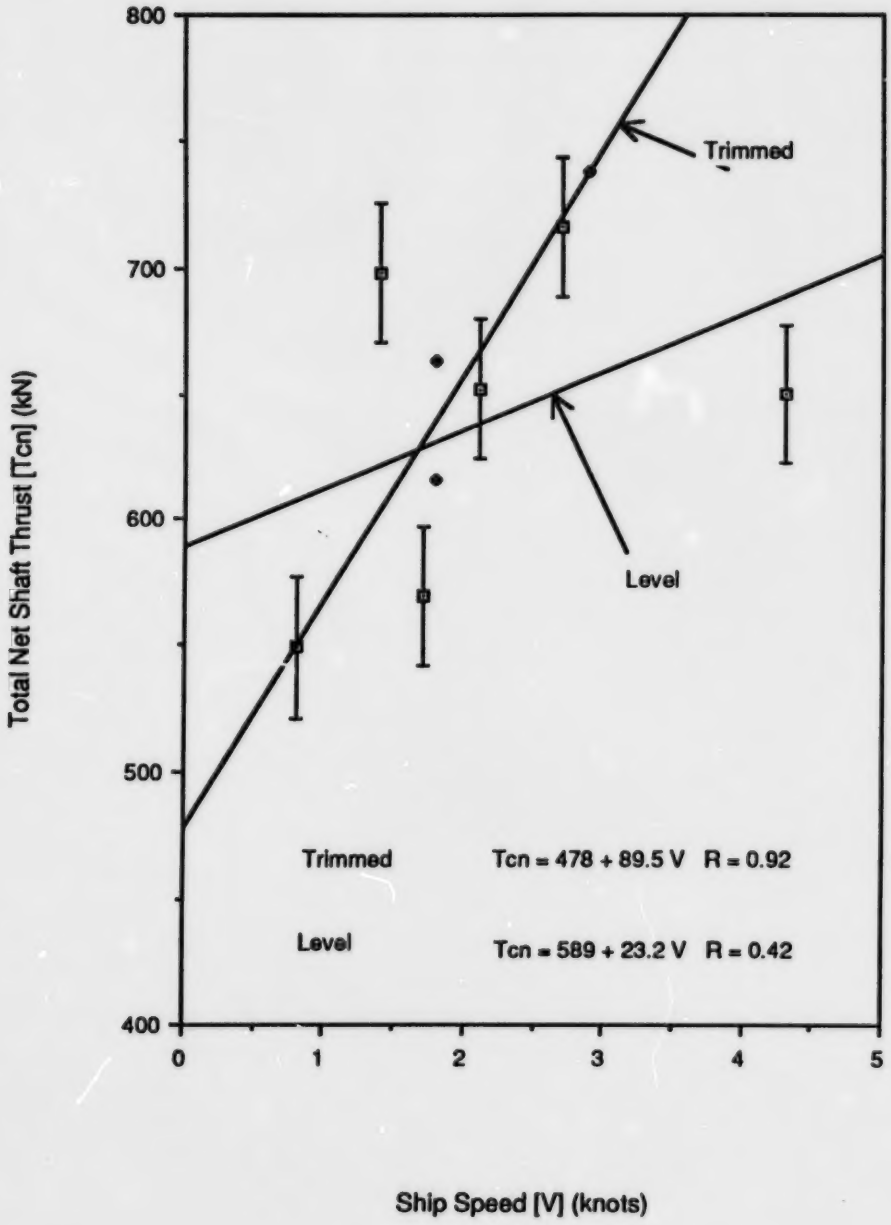


Figure 5.2 Total Net Shaft Thrust vs Ship Speed: All Data



A linear regression line has been fitted to both sets of data for comparison of performance and gives the following relationships:

For level trim:

$$HPc = 3907 + 668 \times V$$

$$Tcn = 589 + 23.2 \times V$$

For the trimmed condition:

$$HPc = 3362 + 668 \times V$$

$$Tcn = 478 + 89.5 \times V$$

It is to be noted that the figures corresponding to zero (0.0) speed indicate the horsepower (thrust) required to overcome static friction (breakaway) and therefore are not included in the fit for the regression.

The comparison of results as presented in Figure 5.1 and 5.2 appears to indicate that the vessel performance is improved with greater strake submergence with a substantial increase in performance above approximately 1.5 knots. The magnitude of this increase is not considered reasonable and is attributed to the data scatter.

In an attempt to better correlate the test results selected data have been re-plotted as indicated in figures 5.3 and 5.4. The data points have been selected such that for the level trim condition snow cover, ice thickness are constant and air temperature is similar to that for the trimmed condition. On this basis then data points from tests 5, 6 and 7 are compared with points from tests 10, 12, and 13.

Figure 5.3 Total Shaft Power vs Ship Speed: Selected Data

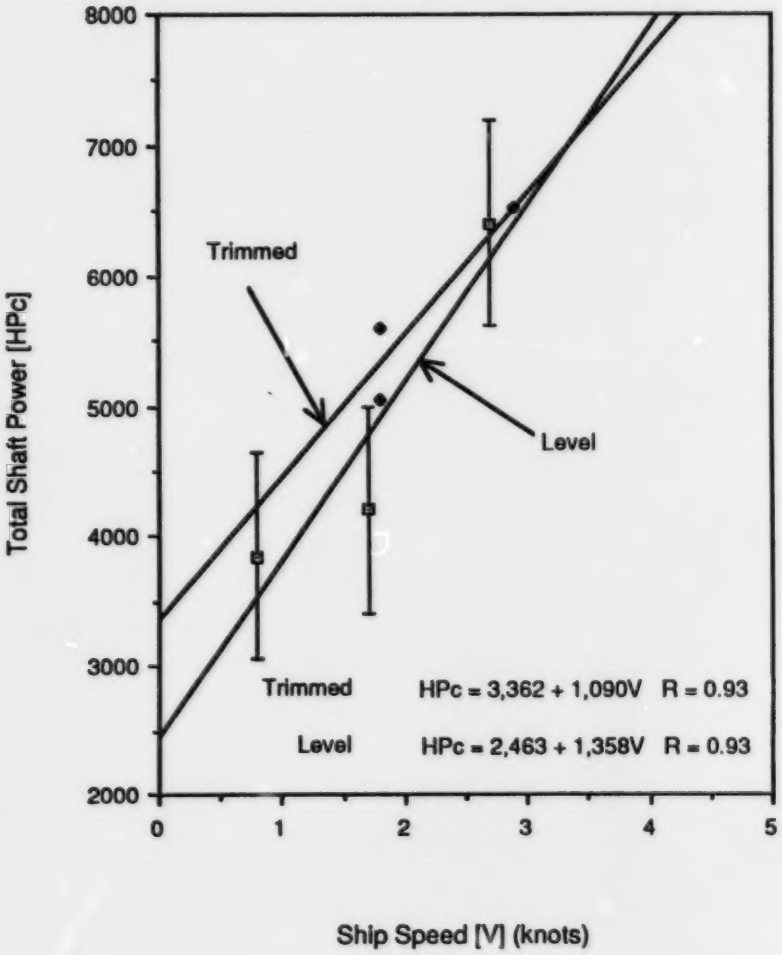
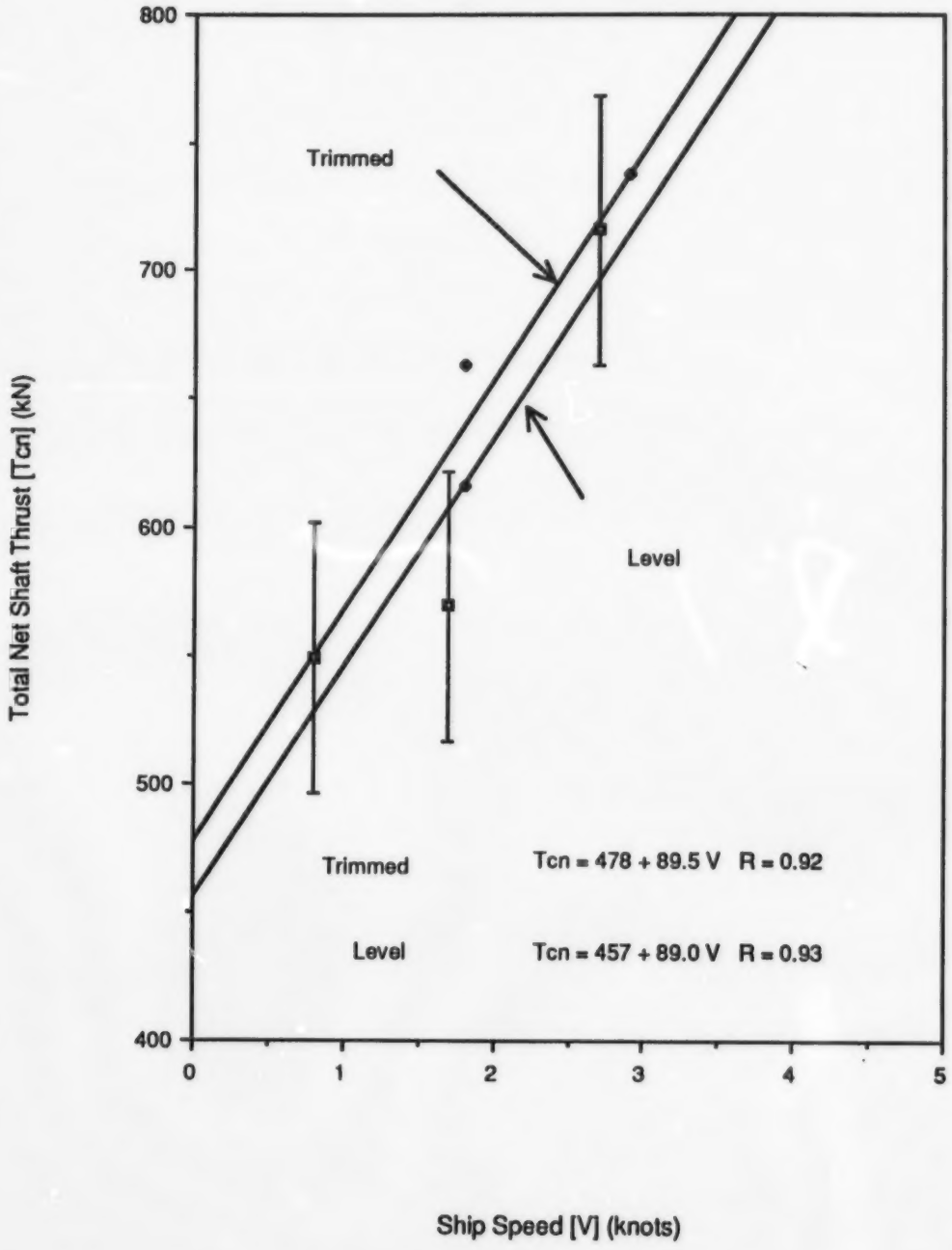


Figure 5.4 Total Net Shaft Thrust vs Ship Speed: Selected Data



Again, applying linear regression techniques, the following relationship between power (thrust) and speed has been determined as follows:

For level trim:

$$HPc = 2,463 + 1,358 \times V$$
$$Tcn = 457 + 89.0 \times V$$

and for trimmed waterline as previously:

$$HPc = 3,362 + 668 \times V$$
$$Tcn = 478 + 89.5 \times V$$

Examination of Figures 5.3 and 5.4 again indicate an improvement in icebreaking performance with increased strake immersion. However, the scatter of the data is such that a standard deviation of one for the level trim regression line, as shown by the error bars, overlaps the majority of the data for the trimmed condition. Based upon the "Carter" model predictions for this hull form, an improvement in icebreaking performance of 3.5% based on power is expected at the trimmed waterline over that at level trim for the vessel.

Comparisons were made between the results on these tests and those conducted on the CCGS Ann Harvey (another type 1100 icebreaker) by Wartsila in March 1989. However, the ice conditions during the Ann Harvey trials were significantly different from those for the Laurier trials, and a reasonable comparison could not be obtained. Therefore, comparisons should be made by executing an analytical model, such as the "Carter" model, on both the Ann Harvey and the Laurier, using the measured ice conditions. This comparison is presented in Reference 6.

5.2 Turning Performance

Figures 5.5 and 5.6 illustrate the turning performance of the CCGS *Sir Wilfrid Laurier*. For the first test (Figure 5.5) the rudder was set to 0° after breaking out of the channel until a constant speed was attained in the level unbroken ice sheet. The rudder was then set to 35°; however, the vessel did not turn appreciably under these conditions. Therefore, on the second test (Figure 5.6) the rudder was maintained hard over after breaking out of the track. In this case the vessel also did not turn significantly once steady speed was attained in the level ice. Therefore, a turning diameter could not be computed.

5.3 Analysis of Video

An analysis of the video tape taken during the trials revealed a number of interesting results:

1. The strakes appeared to be too far aft and too high above the operating water line to be fully effective in breaking the ice. Therefore, the majority of the ice was broken forward of the strakes.

2. The vessel trims approximately 500 mm while breaking level ice. This trim changes the orientation of the strakes to a higher vertical position such that they are less effective.

3. On occasion during level ahead icebreaking sections of the ice sheet were broken by the strakes. When this occurred the breaking mode was in bending and the broken ice pieces were 2-3 metres wide. Since this occurred only occasionally, due to the location of the strakes, the effect of strakes could not be fully realized.

4. Ice pieces broken by the bow structure forward of the strakes were crushed by the strakes.

5. The strakes appeared to orientate the broken ice pieces such that there was little ice contact with the hull aft of the strakes and this possibly reduced the frictional resistance of the ice on the hull in this area.

Figure 5.5 Turning Performance Test Results: Run 1

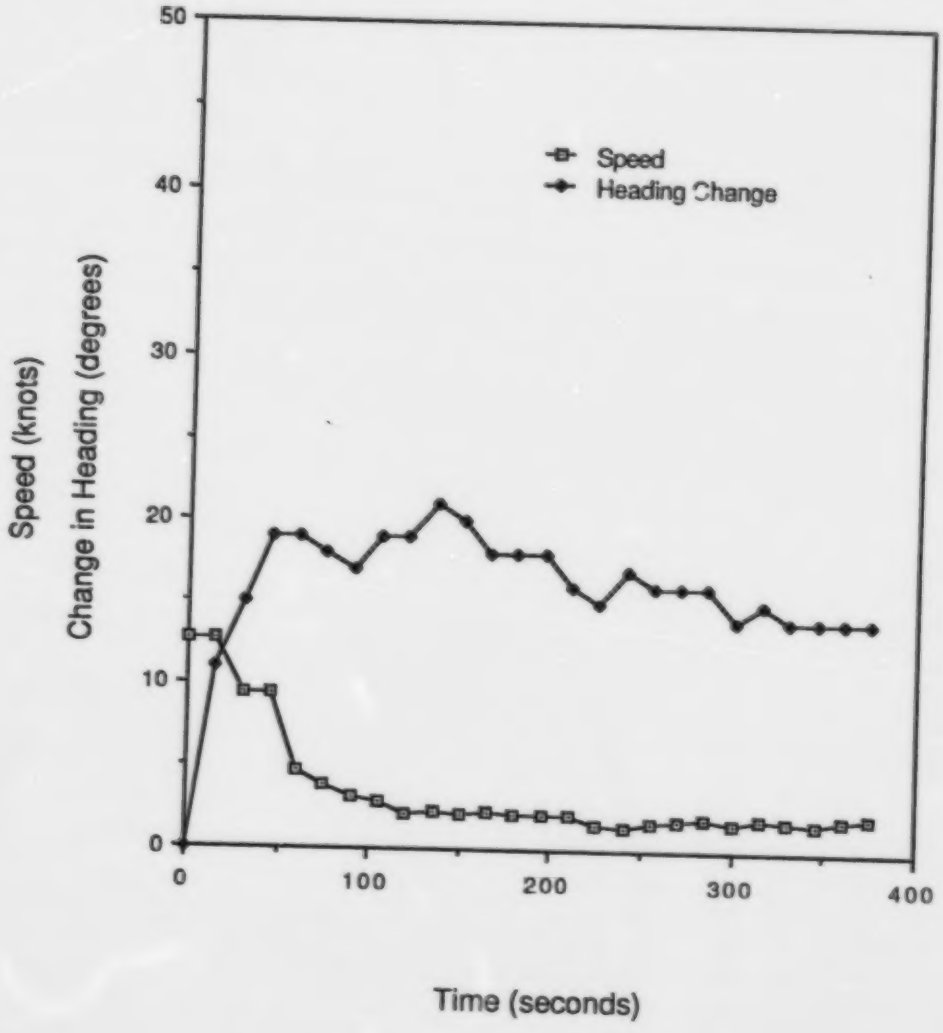


Figure 5.6 Turning Performance Test Results: Run 2

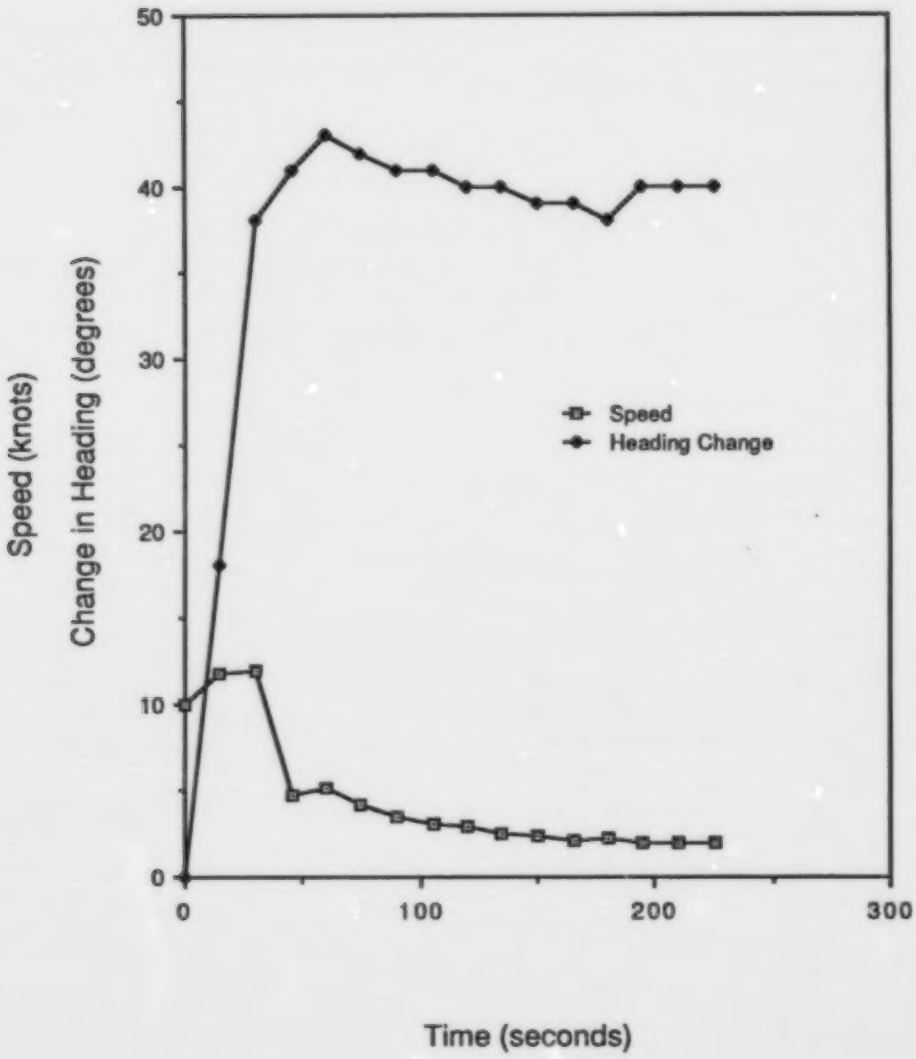


Table 5.3 Turning Performance Data: Run 1

FIRST RUN
DATE: February 8, 1990
TIME: 23:00
LOCATION: 1 NM West of Tracks 3 and 4
ICE CONDITIONS:

Thickness:	**0.85 m**
Snow Cover:	**0.15 m**
Flexural Strength:	**710 kPa**
Young's Modulus:	**1,980 kPa**

DESCRIPTION	HEADING (Degrees)	SPEED (Knots)	Time (Seconds)	TOTAL CHANGE OF HEADING (Degrees)
Heading Down Broken Channel	329	12.8	0	0
Rudder 35°	318	12.8	20	11
Breaking out of channel	314	9.5	40	15
Level Ice	310	9.5	60	19
	310	4.7	80	19
	311	3.9	100	18
	312	3.2	120	17
	310	2.9	140	19
	310	2.2	160	19
Centred Rudder	308	2.3	180	21
	309	2.2	200	20
	311	2.3	220	18
	311	2.1	240	18
Rudder set to 20 degrees	311	2.2	260	18
	313	2.2	280	16
	314	1.6	300	15
	312	1.4	320	17
No turning detected	313	1.7	340	16
	313	1.8	360	16
	313	2.0	380	16
	315	1.7	400	14
	314	2.0	420	15
	315	1.8	440	14
	315	1.7	460	14
	315	2.0	480	14
	317	2.2	500	12
	315	2.3	520	14
	315	2.5	540	14
	315	1.5	560	14
	315	1.9	580	14
	315	Stopped	600	14

Table 5.4 Turning Performance Data: Run 2

SECOND RUN
DATE: February 8, 1990
TIME: 23:30
LOCATION: 1 NM West of Tracks 3 and 4

ICE CONDITIONS:

Thickness:	**0.85 m**
Snow Cover:	**0.15 m**
Flexural Strength:	**710 kPa**
Young's Modulus:	**1,980 kPa**

DESCRIPTION	HEADING (Degrees)	SPEED (Knots)	TIME (Seconds)	TOTAL CHANGE OF HEADING (Degrees)
Heading Down Broken Channel	296	10.0	0	0
Rudder 20°	278	11.8	20	18
Breaking out of channel	258	12.0	40	38
Level Ice	255	4.7	60	41
	253	5.1	80	43
	254	4.1	100	42
	255	3.5	120	41
	255	3.1	140	41
	256	2.9	160	40
	256	2.5	180	40
	257	2.3	200	39
	257	2.1	220	39
	258	2.2	240	38
Stopped Turning	256	1.9	260	40
	256	2.0	280	40
	256	2.0	300	40
	256	2.0	320	40
	256	2.3	340	40
	256	2.3	360	40
	256	2.2	380	40
	256	1.9	400	40
	256	2.2	420	40
	256	2.1	440	40
	256	1.9	460	40
	256	1.9	480	40
	256	1.7	500	40
	256	2.0	520	40
	256	Stopped	540	40

6. CONCLUSIONS AND RECOMMENDATIONS

1. The data collected was insufficient to draw definite conclusions as to the success of the strakes in reducing ice resistance. From analysis of a small data subset (3 data points in a trimmed and 3 points in a level condition) in which ice conditions were constant it appears that the strakes may decrease the resistance slightly; however, the scatter in the data is of the same order as the decrease, and therefore, definite conclusions cannot be drawn. Since the expected improvement from the strakes is relatively small, and in view of the typical scatter in full scale ice testing, considerably more ice test data would be required to determine if there is a statistically significant difference with the strakes. In addition, for an accurate comparison against a "strakeless" vessel, an unmodified vessel should be tested in parallel, as the trimmed condition is a poor comparison and just introduces another uncertainty in the analysis. Therefore, it is recommended that such tests be conducted.

2. It appears that if the strakes were positioned further forward and lower than their present location, they would be more effective in breaking the ice.

3. The bow section of the vessel rises approximately 0.3 - 0.5 metres while level icebreaking ahead in 0.8 - 0.95 metres of ice. This displacement of the bow should be taken into account when deciding on the optimum position and inclination of bow appendages, such as strakes, used to decrease icebreaking resistance. It is recommended that further tests be conducted with strakes located in such a position.

4. Because of the uncertainty of the estimation of the ice strength calculated from temperature and salinity measurements, it is recommended that cantilever beam tests be conducted on site in future trials.

7. REFERENCES

1) Carter, J.E., "Strake Application on a Canadian Coast Guard Ship", July 1990, TDC Report, TP #10553E.

2) Lane, J.F, "On The Strengths of Sea Ice and a Correlation Between the Various Strength Tests", Report LTR-LT-104, National Research Council Canada, Sept. 1979.

3) Lane, J.F, "On Estimating The Average Strength of Level Sea Ice", Report LTR-LT-109, National Research Council Canada, Feb. 1980.

4) Bernard Michel, Rene O. Ramseier, "Crystallographic Analysis and Theoretical Flexural Strength of River Ice", University of Laval, Department of Civil Engineering, Ice Mechanics, Rapport T-6, 1969.

5) Bernard Michel, Marc Drouin, "Resistance "In Situ" De La Glace in Flexion", Universite Laval, Department Genie Civil, Mecanique des Glaces, Rapport T-5, mars 1969.

6) Comfort, G. and Abdelnour, R., "Ice Conditions At A Proposed Dock Site at Grand Anse, Saguenay River", Arctec Canada Internal Report, 1980.